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A microcomputer-based instrument for applications in platinum resistance thermometry

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Abstract. Platinum resistance thermometers are widely used in temperature measurements not only for calibration purposes but also in industrial applications. A new automatic instrument is described which can determine the actual value of the resistance of a platinum resistance thermometer in less than 0.52 s with a resolution of 8 PPM. The self-heating index can also be determined and the instrument is able to multiplex up to eight different platinum resistances. The temperature is calculated by using the interpolation formulae defined by the International Practical Temperature Scale of 1968 (IPTS-68).

1. Introduction

The problem of temperature measurement using platinum resistance thermometers is that of measuring resistance ratios. However, in this case, the test has to be done in such a way that secondary effects such as self-heating, Seebeck effect and Peltier effect introduce no significant errors in the measurement (National Bureau of Standards 1973) and, at the same time, the test must be done as quickly as possible, especially in industrial and control applications, in order to avoid unnecessary delays in establishing the temperature.

A fast instrument is also useful to take comparative readings from a number of thermometers at effectively the same time.

The response time is an important parameter in any sensor. In a platinum resistance thermometer it is particularly significant because it is related to the conditions in which the thermometer operates (position, pressure, insertion depth, etc) and also to its physical condition (materials accumulated on the surface of the sensor, cracking of cement used to insulate and/or support the sensing element, etc) (Kerlin 1981). British Standard 1904 (British Standards Institution 1964) specifies that to measure response time, the time constant of the instrument must not exceed 1/10 of the overall time constant of the sensor: hence, for industrial platinum resistance thermometers with a time constant of the order of 8 s, the measurement must be done with an instrument of time constant 0.8 s maximum.

This paper describes an instrument for resistance ratio measurements. It produces one reading in 0.52 s, eliminates all of the above mentioned systematic errors and has an uncertainty of eight parts per million. It is able to multiplex up to eight thermometers within 4.16 s and, if required, it can compute the actual value of temperature according to IPTS-68 (National Physical Laboratory 1976). The self-heating index can also be measured. The instrument was built in collaboration with Rosemount Engineering Company plc.

2. The method

Traditionally, bridge circuits have been used in association with platinum resistance thermometers (Barber *et al* 1973). For the highest accuracy four-wire connections are essential. The Smith and Mueller (Mueller 1941) bridges were designed to allow this. If a bridge is energised by DC, the current must be reversed and two readings taken in order to eliminate the effect of Seebeck EMFs; but if it is energised by AC, the inductance and self-capacitance of the thermometer affect the balance. Rogai and Johnston (1967) devised an ingenious compromise using AC modulated at 5 Hz in a transformer ratio bridge. Nevertheless, all these bridges are manually balanced and their use in automatic measurements is not possible.

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The changing economics of instrument manufacture are increasing the cost of accurate, stable resistors and accurate inductive dividers at the same time as the cost of analogue-to-digital converters is falling rapidly. The new instrument uses only one standard resistor which carries the same current as the thermometer. A purpose-built circuit then converts the voltage ratio to a time ratio and hence to a number.

The instrument makes use of a microcomputer to take a number of readings in rapid succession and compute the average. It is shown in the appendix how this can be arranged to eliminate most of the errors, even without the use of expensive components except for a single, standard resistor.

A complete model for the potentiometric method can be seen in figure 1: e_i, spurious EMF at i, e.g. Seebeck EMF; r_i, lead and contact resistance at i; R_x, resistance of the unknown resistor; R_s, resistance of the standard resistor; V_x, voltage appearing at potential terminals of R_x; V_s, voltage appearing at potential terminals of R_s.

With a high input impedance circuit to measure V_x, V_s, negligible current passes through r_2, r_3, r_6, r_7 and they do not appear in the expression for V_x and V_s.

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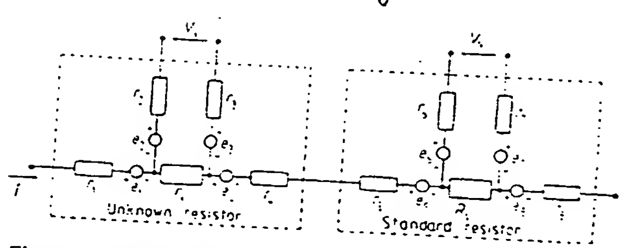

Figure 1. Potentiometric method.

Taking two pairs of readings with currents in opposite senses, the following are obtained:

$$V_{x1} = I_1 R_x + e_2 - e_3 \tag{1}$$

$$V_{x2} = -I_2 R_x + e_2 - e_3 \tag{2}$$

$$V_{s1} = I_1 R_s + e_6 - e_7 \tag{3}$$

$$V_{s2} = -I_2 R_s + e_6 - e_7. \tag{4}$$

The average of the absolute values gives

$$|\overline{V_x}| = (I_1 + I_2) R_x / 2 \tag{5}$$

$$|\overline{V_s}| = (I_1 + I_2) R_s / 2. \tag{6}$$

By eliminating I_1 and I_2 we have

$$R_x = R_s |\overline{V_x}| / |\overline{V_s}|. \tag{7}$$

This method will also reject other sources of systematic error like Kelvin effect in the leads and small currents passing

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through r_2, r_3, r_4 and r_5 provided that they remain constant during the measuring time. This can easily be demonstrated by including their effects in the voltage sources e_2, e_3, e_4 and e_5.

Also the unwanted Peltier effect is cancelled out because of the averaging of two readings with different current senses. Neither is it necessary for the forward and reverse currents, I_1 and I_2, to be exactly equal, provided they do not change between the measurement of V_s and V_t.

It is shown in the appendix that the same sequence of readings will also eliminate errors due to offset voltages and bias currents in the amplifiers and energising circuit.

3. The system – general description

Figure 2 is a basic block diagram of the system which illustrates the functional blocks and their data and control signals.

The energising circuit, under control from the microcomputer, produces suitable voltages on R_s (terminals 1 and 2) which energise the resistances R_s and R_t connected in series. The terminal marked 3 is a high-impedance one which provides a 'virtual ground' for the low common mode voltage at the input of the selector circuit. The voltages are +0.1 V and –0.1 V for normal resistance measurements and +5 V for self-heating tests (can be adjusted).

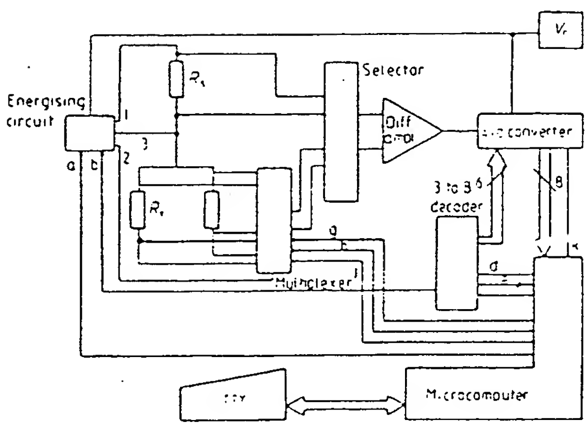

Figure 2. Functional block diagram.

The selector circuit consists of CMOS switches which break-before-make, have low leakage current, and are TTL compatible. It connects either R_s or R_t to the differential amplifier.

A 17-bit dual ramp A/D converter supplies the data signal to be sent to the microcomputer. This was specially designed for high relative accuracy, but is cheaper than an A/D converter with 17-bit absolute accuracy. It is able to produce one reading in no more than 80 ms and the integration time of 40 ms produces a series mode rejection to interference of 50 Hz or harmonics.

In order to reduce the computation time, the A/D converter produces the sum of two consecutive readings by not resetting its counter between the first and second readings. At the end of each conversion cycle a data ready signal ('k') is sent to the microcomputer.

The reference voltage for both the energising circuit and the A/D converter is the same and is provided by a precision, low-noise temperature-stabilised monolithic Zener diode.

The microcomputer performs the following operations.

(i) Accepts commands from either its own keyboard or a teletype (TTY).

(ii) Sends signal 'a' to select the current sense in resistance measurements.

(iii) Produces signal 'b' for high-current mode in self-heating tests.

(iv) Sends signal 'c' to select either R_s or R_t.

(v) Produces signals 'd', 'e', 'f' to control the operation of the A/D converter.

(vi) Sends signals 'g', 'h', 'j' to control the multiplexer.

(vii) Reads the data coming from the A/D converter after the data-ready signal is received.

(viii) Calculates the temperature in accordance with IPTS-68 in its amended edition of 1975.

(ix) Prints out the results on a teletype or on a 20-character printer in the microcomputer.

4. Circuit details and analysis

4.1. Energising circuit

It can be seen from figure 3 that an earthed current source introduces different common mode signals depending on the voltage under measurement. Common mode signals at the amplifier input can be minimised if a floating current source is used and the junction of R_s and R_t is at earth potential.

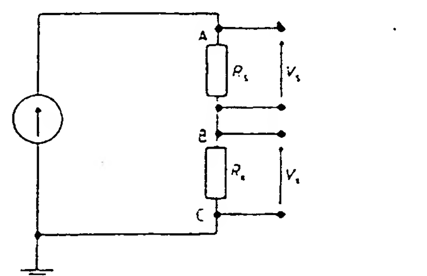

Figure 3. Common mode signals produced by earthed current source. Measuring V_t the common mode signal is $V_s + V_t/2$; measuring V_s the common mode signal is $V_s/2$.

The normal energising current was chosen to be as high as possible for maximum signal-to-noise ratio and, at the same time, low enough to avoid errors introduced by self-heating. A typical self-heating index is 8 Ω W^{-1} for a 100 Ω sensor (Kerlin *et al* 1978); then, for an error of 0.001 Ω (10 parts per million), the maximum allowable power which can be dissipated in that resistance is 0.125 mW. The selected energising voltage of about 0.1 V dissipates a power of 0.1 mW in 100 Ω.

Consider the circuit in figure 4. The operational amplifier OA_1 and the switches S_1 and S_2 produce +1 V or –1 V depending on the control signal applied to the switches. When

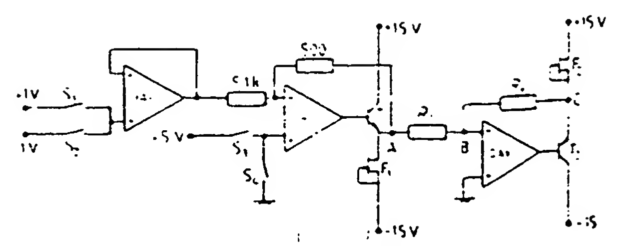

Figure 4. Floating constant current source.

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measuring resistances. S_3 is open and S_4 is closed and the voltage at the end A of R_s is $-$ or $+0.098\,04$ V. The operational amplifier OA_1 keeps B at a potential equal to its offset voltage (typically 1 mV) and, because of its very low bias current, no important error is introduced. It acts as an amplifier of gain $-R_t/R_s$. So, if the voltage applied to R_s (about 0.1 V) is able to produce a full-scale output from the A/D converter, then, in terms of the resistances, the full scale is given by the value of R_s, i.e. the maximum resistance which can be measured with this instrument will be equal to the standard resistor R_s. Another important characteristic of this circuit is that both R_s and R_t are connected to low-impedance points. This is essential in order to avoid electromagnetically induced noise.

The high current for self-heating tests is supplied by the transistors T_1 and T_2. In this case S_3 is closed, S_4 is opened and the current through the resistances is about $5/R_s$ (for R_s having a typical value of 100 Ω the current is 50 mA).

F_1 and F_2 are field effect transistors with $I_{DSS} > 10$ mA. They define the operating conditions of T_1 and T_2 with a very high rejection to noise in the power supply.

4.2. *Differential amplifier*

The differential amplifier is a classical design comprising three low-noise, JFET-input operational amplifiers and having a gain of ten. Its feedback network is made with high-stability, wire-wound resistors.

4.3. *A/D converter*

The A/D converter is a 17-bit dual-ramp converter fully controllable by the microcomputer, with an 18-bit counter. When the conversion is complete, a data-ready signal is sent to the microcomputer and the count in the counter is proportional to the modulus of the input signal and inversely proportional to the reference voltage.

This converter is unconventional because the counter is not reset after each conversion: it accumulates the counts during two successive conversions which are performed with the energising current reversed. The capacity of the counter is 262 144 and the total count represents twice the average input voltage as required by equation (7). If the positive and negative reference voltages differ slightly the effect will be the same as if the forward and reverse currents differ slightly and will not invalidate the resistance ratio measurement.

Errors introduced by offsets in the integrator and comparator are cancelled out by the averaging of the two readings of opposite polarities on each resistance and long-term stabilities of the reference voltage and of the frequency of the oscillator are not critical because they affect the counts corresponding to V_s and V_t in the same ratio (see equation (7)).

4.4. *Multiplexer*

Figure 5 illustrates the functions of the multiplexer. This circuit not only connects one of the resistances R_t to the selector circuit, but also completes its connection to the energising circuit

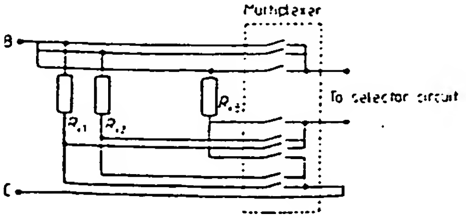

Figure 5. Connections of the multiplexer.

(output of operational amplifier OA_1). Up to eight different thermometers can be connected to the system and selected in any specified order.

4.5. *Microcomputer*

The microcomputer is type AIM-65 manufactured by Rockwell International. This has a BASIC language interpreter and 4k RAM which is enough for the complete operation of the system. It has two ports: one of them is used as output port for control of the system, and the other is used to transfer data from the A/D converter. An additional interrupt input is used for the data-ready signal and to synchronise the system in time constant measurements. The built-in alphanumeric keyboard, 20-character printer and teletype driver allow the user to select the printing format and the method of typing in the parameters of the test (value of the standard resistor and the R_0, B_4, E_4, α and δ values of the thermometer).

The use of BASIC in the development stages allowed more concentration on the electronic circuits, because changes in the software could be implemented very easily. The complete instrument could, of course, use a dedicated microprocessor, but this would reduce the flexibility in adapting the instrument to special applications and using the measured temperature in further calculations. This work will be described in a forthcoming paper.

5. Software

The software consists of a set of programs written in BASIC. The main program controls the sequence of operations necessary to obtain readings proportional to V_s and V_t and, given the value of R_s, calculates the value of R_t. From this value and the parameters of the platinum resistance thermometer it calculates the actual temperature by using the interpolation formulae (IPTS-68, 1975). For this calculation the program separates the actual range of temperatures into two: one from 90.188 K to 273.15 K, and the other from 0 °C to 630.74 °C and uses two subroutines depending on the range of temperatures. To do this, the resistance of the platinum resistance thermometer is compared with its value at the triple point of water R_0.

For self-heating tests, the computer takes one reading, puts the system in high-current mode (supplies 50 mA during about 120 s) and then takes a second reading of the resistance (it is actually taken 0.075 s after the high current is removed). The self-heating index, defined as the change in the resistance of a platinum resistance thermometer per unit of power dissipated in it and expressed in units of Ω W^{-1}, is calculated by assuming that the power is dissipated by the energising current in a resistance with the last measured value.

To measure the time constant of a thermometer, it is suddenly plunged into a bath of hot liquid. The program is initially in a 'wait for interrupt' loop. The interrupt signal is produced by a switch controlled by the operator at the moment at which the sensor touches the liquid.

0.075 s after the interrupt, the computer takes its first reading and continues to take readings every 0.52 s until 49 readings have been completed. The 50th and final reading is taken after a further 120 s. The time constant is defined as the time necessary for the sensor to reach 63.2% of the final reading and is calculated by the microcomputer.

6. Results of performance tests

Test 1

To assess the accuracy of the system, two resistors were compared: R_s, standard resistor no 13367 manufactured by H Tinsley & Co. Ltd, nominal value 100 Ω and R_t, resistance

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box no 760 693 manufactured by Sullivan Ltd. nominal value 10 Ω, and fitted with terminals for four-wire connection.

In a sample of 100 consecutive readings the statistical results were

$$R_x/R_s\ (\text{mean}) = 0.100\,078\,2$$

$$\text{Standard deviation} = 0.000\,010\,4$$

$$\text{Maximum deviation from the mean} = 0.000\,028\,2.$$

The same ratio was calculated from values obtained with a Datron voltmeter, model 1071, serial no 7414:

$$R_x = 10.007\,48\ \Omega$$

$$R_s = 100.0018\ \Omega$$

$$R_x/R_s = 0.100\,073.$$

Thus, the mean value differs from the results obtained with the Datron voltmeter by 0.000 005 2, which represents 5.2 PPM of full scale or less than 1 LSB.

For the 10 Ω range the Datron voltmeter uses a current of 10 mA.

Test 2
Two similar standard resistors were compared but now obtaining a ratio and its inverse.

After 20 consecutive readings, the results were

$$R_1/R_2\ (\text{mean}) = 0.999\,851\,5$$

$$\text{Standard deviation} = 0.000\,007\,3$$

$$R_2/R_1\ (\text{mean}) = 1.000\,158\,5$$

$$\text{Standard deviation} = 0.000\,006\,5.$$

The first ratio differs from the inverse of the second by 0.000 01 or 10 PPM of full scale (1.3 LSB).

The same measurements were made with a Rosemount bridge model VLF-51, serial no VLF51-187:

$$R_1/R_2 = 0.999\,859$$

$$R_2/R_1 = 1.000\,162.$$

The average of the first ratio and the inverse of the second were taken and the resulting value was considered as the best estimate:

$$\text{Best estimate of } R_1/R_2 = 0.999\,848\,5.$$

Thus, the measured ratio R_1/R_2 differs from the best estimate by 3 PPM or 1/2 LSB, and the measured ratio R_2/R_1 differs from the inverse of the best estimate by 7 PPM or 1 LSB.

The current was adjusted to 1 mA in both cases.

Test 1 was not performed with this bridge because the uncertainties of the VLF-51 are too high at resistance ratios of the order of 10:1.

Test 3
Self-heating and time constant tests were made on three platinum resistance thermometers in an oil thermal bath at 30 °C.

(i) Thermometer model E12382 S/N 11139 manufactured by Rosemount Engineering plc:

$$\text{Self-heating index} = 5.05\ \Omega\ \text{W}^{-1}$$

$$\text{Overall time constant} = 17.6\ \text{s}.$$

(ii) Thermometer model E12382 S/N 16276 manufactured by Rosemount Engineering plc:

$$\text{Self-heating index} = 5.81\ \Omega\ \text{W}^{-1}$$

$$\text{Overall time constant} = 19.8\ \text{s}.$$

(iii) Thermometer model BSE712-F4-6008-2 S/N 14076 manufactured by Rosemount Engineering plc:

$$\text{Self-heating index} = 14.29\ \Omega\ \text{W}^{-1}$$

$$\text{Overall time constant} = 5.8\ \text{s}.$$

The first two thermometers are of the same type with the exception only of their lengths. This explains their similar characteristics.

Thermometer (iii) is much smaller than the others. It has less mass with a fast response but also less surface area with a lower thermal conductivity (Eckert *et al* 1972) (consequently a higher self-heating index).

Test 4
The multiplexer was also tested. One standard resistor was used as unknown resistor and connected each time to a different input channel. No important differences were noted with respect to the results of test 1.

Test 5
Tests 1 and 2 were repeated but now using leads 25 m long to connect R_x and no differences were noticed in the statistical results.

7. Conclusions

(i) This instrument, even at its prototype stage, offers a cheap and reliable substitute for normal bridges with the advantage of its automatic operation.
(ii) The multiplexing facilities enable it to be used for correlating temperatures at different points in a process.
(iii) Because of its speed, it can be used for control purposes by programming the microcomputer to take decisions according to a defined strategy.
(iv) The use of DC techniques eliminates errors introduced by reactive components in the platinum resistance thermometer.
(v) The accuracy of the instrument is approaching the limit set by the quantisation, which is 7.6 PPM.

Appendix

A.1. Effects of offset voltages in switches and operational amplifiers

A complete analysis of the effects of the selector circuit and differential amplifier can be done with the help of figure 6: I_1, I_2, energising currents: V_c, common mode voltage introduced by offsets in the energising circuit: S, switches to connect R_s to the amplifier: X, switches to connect R_x to the amplifier: V_{0ij}, total offset voltage introduced by one switch and one operational amplifier: A_j, one-side gain of the differential amplifier, where by definition the differential gain $A_d = (A_1 - A_2)$ and the common mode gain $A_c = (A_1 - A_2)$.

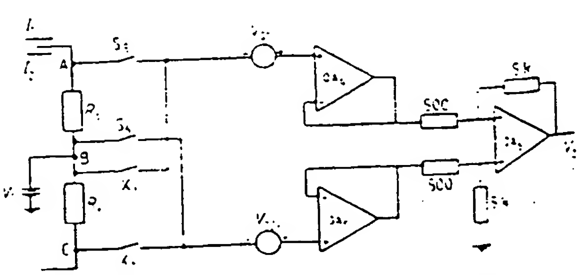

Figure 6. Effects of offset and common mode voltages.

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When the resistance R_x is connected, for current I_1

$$V_1 = (V_c + I_1 R_x - V_{01})A.$$

$$V_2 = (V_c + V_{02})A$$

and: the differential voltage is $V_d = V_1 - V_2$ similarly, for current I_2, after the average of the absolute values is taken.

$$|\overline{V_x}| = (I_1 - I_2)R_x A \tag{8}$$

and

$$|\overline{V_s}| = (I_1 + I_2)R_s A. \tag{9}$$

Then, after dividing equation (9) by equation (8)

$$R_x = R_s |\overline{V_x}| / |\overline{V_s}|.$$

So, no errors are introduced by the offsets of the first two operational amplifiers and of the switches or by the common mode voltage V_c provided it remains constant.

A.2. *Effects of leakage currents and charge injection in switches, and bias currents in operational amplifiers*

The typical leakage current of the switches used in the multiplexer and in the selector circuit is 0.03 nA, and the typical bias current of the operational amplifier is 0.05 nA.

Consider figure 7. I_a, bias current of the operational amplifier OA_3 in the energising circuit; I_b, I_c, $I_{c'}$, leakage currents in multiplexer switches; I_d, I_e, I_f, I_g, leakage currents in selector circuit switches; I_h, I_k, bias currents in operational amplifiers of the differential amplifier.

In the case of terminal B of R_x, it is necessary to take into account the effect of the currents: $I_a = 0.05$ nA, $I_{c'} = (6 \times 0.03)$ nA, $I_d = 0.03$ nA, $I_f = 0.03$ nA, $I_h = 0.05$ nA. This gives a total current of 0.34 nA; which represents 0.34 PPM with respect to 1 mA energising current. However, the actual effect is even smaller, as can be shown.

Currents I_b, I_c, I_e, I_g introduce no errors because they do not affect the common current through R_s and R_x.

Changes in the sense of the energising current will not produce significant changes in either the sense or the magnitude of currents I_a, $I_{c'}$, I_d, I_f, I_h, I_k. When the energising current is I_1

$$V_{s1} = R_s I_1$$

$$V_{x1} = R_x(I_1 - I_a - I_{c'} - I_d - I_f - I_h).$$

When the energising current is I_2

$$|V_{s2}| = R_s I_2$$

$$|V_{x2}| = R_x(I_2 + I_a + I_{c'} + I_d + I_f + I_h).$$

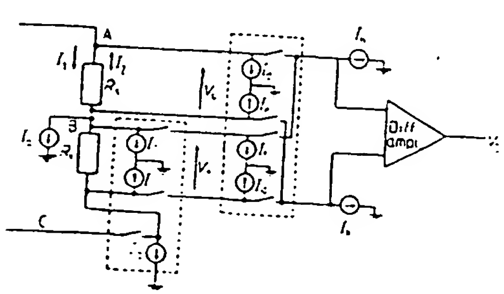

Figure 7. Effects of leakage currents.

The average becomes

$$|\overline{V_s}| = R_s(I_1 - I_2)/2$$

$$|\overline{V_x}| = R_x(I_1 + I_2)/2.$$

So, again, the errors are cancelled out.

The only effect of charge injection due to switches is to produce a transient at the switching time, but the actual conversion in the A/D converter is delayed in order to avoid this transient.

Acknowledgments

The authors wish to acknowledge the facilities provided by the Department of Electrical Engineering and Electronics at UMIST and the cooperation of Rosemount Engineering plc. They also recognise the contribution of Mr S K S Shirazi who built the first prototype of this instrument.

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